Swede midge (*Contarinia nasturtii*)

Review by Daniel Wilson and Rosemary Collier, University of Warwick for AHDB

1.1 Life cycle and biology

The swede midge, *Contarinia nasturtii* Kieffer (Diptera: Cecidomyiidae), is a small galling fly (1.5–2 mm) whose larvae feed on various members of the Brassicaceae family, including a number of brassicaceous weeds and economically-important crop species (*e.g.* cabbage, cauliflower, broccoli, kale, swede and oilseed rape) (Barnes, 1946; 1950; Readshaw, 1961; Hallett, 2007). The species occurs mainly in northern Europe, southwestern Asia and North America (Barnes, 1946; Chen *et al*., 2011). In the UK, *C. nasturtii* is recognised as a local and sporadic crop pest. Infestations are usually minor but can vary considerably in severity each year. In North America, *C. nasturtii* is an invasive pest and has become a serious issue (Chen *et al*., 2011). For example, individual crops can incur considerable damage, with up to 85% losses (Hallett and Heal, 2001). In some cases, it is possible that the damage caused by swede midge is misdiagnosed due to having similar symptoms to a number of other plant conditions (*e.g.* physiological/nutritional problems) (Chen *et al*., 2011; Hodgdon *et al*., 2017).

Typically, the swede midge undergoes three generations in a year. However, in warm years the species may complete a fourth or partial fourth generation (Readshaw, 1966; Hallett *et al*., 2008). In the UK, the larvae of the third generation overwinter in cocoons in the soil and pupate the following spring in response to rises in temperature and soil moisture (Readshaw, 1966). Adults may emerge as early as late May but often begin to fly during early to mid-June (Lole, 2005). Some overwintering larvae may not develop into adults during the first year and instead emerge the following year (Readshaw, 1966; Des Marteaux *et al*., 2015). Adults have short life spans, often only 1–3 days, in which time they mate and lay eggs on their host plants.

Female midges lay approximately 100 eggs in their lifetime in batches of up to 50 eggs on the developing parts of plants (*e.g.* on terminal buds, petioles of young leaves or inflorescences) (Barnes, 1946; 1950; Allen *et al*., 2009). Eggs generally hatch in three to nine days. Larval development then takes between one to several (>three) weeks and can be supported by almost all parts of the plant, but often by the plant meristem (Barnes, 1946). The larvae feed by secreting salivary enzymes that act to breakdown plant cells (Readshaw, 1961). When fully-developed, third instar larvae relocate (by 'jumping'/falling) to the soil to pupate in a cocoon (Readshaw, 1961). Depending on soil temperature, pupal development can take around one to three weeks, after which the adults emerge from the ground. The swede midge completes its entire life cycle in around a month, therefore in the UK, the

second generation is usually produced in July and the third in August (Lole. 2005). Life cycle duration, however, can vary depending on environmental variables such as temperature, humidity and rainfall (Readshaw, 1966).

The distribution and timing of *C. nasturtii* is also influenced considerably by rainfall and the subsequent levels of soil moisture (Readshaw, 1966; Chen *et al*., 2011). The larvae may cease development and enter periods of dormancy under conditions of drought. Additionally, during periods of drought, mature larvae may reside in cocoons at lower soil levels. After an increase in soil moisture, the larvae return to the soil surface and then re-enter the soil to form new cocoons and pupate. However, when examined alongside soil moisture, different soil types were not found to significantly affect the emergence time of adults (Chen and Shelton, 2007).

The main factors that determine the abundance of *C. nasturtii* are unclear. It is possible that weather conditions (*e.g.* temperature and/or rainfall) and natural enemies could both be important (Abram *et al*., 2012; Des Marteaux *et al*., 2015).

1.2 Detection of *C. nasturtii* and plant damage in the field

In the field, the detection of swede midge can be difficult. Adults do not live for very long (often only a few days) and resemble other closely-related midge species. Additionally, the pupae reside in the soil and the larvae are relatively small (0.3–4 mm) and often feed cryptically on plants (Chen *et al*., 2011). The time of sampling is therefore crucial. For plants exhibiting damage symptoms, the detection of larvae is often the best way to confirm infestation by *C. nasturtii* (Lole, 2005). The defining characteristics of the different life stages of *C. nasturtii* are outlined in Table 1.

In plants, typical damage symptoms by *C. nasturtii* larvae include: swollen, distorted or twisted young shoots and petioles, death of the meristem causing blind heads and growth of the side shoots to cause many-necked plants, brown scarring on the petioles or stems and the development of secondary bacterial rots (Barnes, 1946; 1950; Hallett and Heal, 2001; Allen *et al*., 2009). There can also be a reduction in seed production if plants are infested at the flowering stage (Barnes, 1946). Some of these symptoms may be confused with common physiological conditions (*e.g.* heat stress), nutritional deficiencies (*e.g.* molybdenum deficiency), mechanical plant damage and/or feeding damage by other pest insects (Chen *et al*., 2011; Hodgdon *et al*., 2017).

Table 1. Defining characteristics of the different life stages of *C. nasturtii*.

Adult	Small (1.5–2 mm), greenish-yellow to light-brown in colour. Adults have very hairy wings and females have a distinct elongate ovipositor.
Egg	Very small (0.3 mm), initially transparent and then turn creamy-white as they develop.
Larva	Small maggots, initially 0.3 mm in size but develop to reach 3–4 mm. The larvae are initially translucent and become increasingly yellow–lemon-yellow as they mature. On the underside larvae have a sternal spatula by their mouthparts. This can be observed with a x10 hand lens.
Pupa	The pupa is around 1.3 mm in length and forms cocoons in the soil.

Damage by *C. nasturtii* can be severe, leading to unmarketable crops or entire crop losses (Hallett and Heal, 2001; Chen *et al.*, 2011). In terms of damage thresholds, Stratton *et al.* (2018) found that a single larva was able to cause mild twisting and crown-scarring symptoms of cauliflower, rendering crops unmarketable 52% of the time.

The use of detection tools for *C. nasturtii*, such as sticky traps, blacklight traps, fine-mesh emergence tents, and sweep nets have limited success due to their low efficiency and indiscriminate capturing techniques (Hallett *et al.*, 2007).

However, Hillbur *et al.* (2005) found that a blend of sex pheromones (2S,9S-diacetoxyundecane, 2S,10S-diacetoxyundecane and S-2-acetoxyundecane) extracted from the ovipositors of females could be used to attract adult males in the field with high efficacy and species-specificity. When used in polyethylene dispensers under field conditions in Switzerland, the blend was able to attract male adults for around six weeks (Boddum *et al.*, 2009). Pheromone traps should be placed at 30 cm above the ground, as *C. nasturtii* is a relatively low-flying insect, and individual traps should be at least 50 m apart in the field (Allen *et al.*, 2009).

Pheromone traps can therefore be used to monitor the presence of *C. nasturtii* and the relative numbers in the field. As the traps only attract males, their ability to reduce damage caused by *C. nasturtii* is limited (Hodgdon *et al.*, 2017). Once captured, microscopic identification is required to distinguish between male swede midge adults and other species of fly that may accidentally enter the trap.

However, it may be difficult to accurately identify *C. nasturtii* captured on sticky traps or on the sticky surfaces inside pheromone traps. Instead molecular approaches, such a polymerase chain reaction (PCR)-based method, developed by Frey *et al*. (2004) for *C. nasturtii* identification, may be required.

In a recent study, Boddum *et al*. (2018) demonstrated that certain mixtures of plant volatiles from *Brassica* species were likely to attract adult females. They suggested that these mixtures could be used to develop volatile lures to monitor and control adult females and supplement the use of pheromone traps for adult males.

1.3 Management approaches

Crop rotation

The swede midge has a limited capacity for dispersal. This is because the adults are relatively weak fliers (Hodgdon *et al*., 2019b) and have a short life span. For these reasons, damage can be reduced by ensuring crops are not grown in the same field as, or nearby, to previous infestations over the last two–three years (Chen *et al*., 2009; Chen *et al*., 2011). Where possible, a distance of least one mile between a new crop and a previous infestation is recommended (Hodgdon *et al*., 2017). Crop rotation acts to disrupt the life cycle of *C. nasturtii,* by preventing adults from locating suitable hosts when they emerge from overwintering the following summer (Hodgdon *et al*., 2017). Crop rotation is often the single most effective method to reduce damage by *C. nasturtii* in the field.

Time of planting

In addition to crop rotation or in cases where carrying out adequate rotations are not possible; the earlier planting of crops may help to reduced damage by *C. nasturtii* as larger plants are typically less susceptible to attack (Chen *et al*., 2011). Additionally, when possible, planting *Brassica* crops after the majority of the first generation has emerged (May–June) may help to reduce damage by *C. nasturtii* by restricting the access of the first generation to suitable hosts (Hodgdon *et al*., 2017). In the field, it is also important to remove host weeds and to avoid using *Brassica* cover crops in infested areas, as these will support the development of *C. nasturtii* (Allen *et al*., 2009).

Intercropping

Research at the University of Vermont showed that intercropping broccoli with a number of non-*Brassica* vegetable, herb and cover crop species did not provide sufficient control of *C. nasturtii*, in both laboratory and field experiments.

Host plant susceptibility and resistance

The host range of *C. nasturtii* includes almost all lines of cultivated *Brassica* species. High levels of crop damage are reported for crops such as broccoli, Brussels sprouts, cauliflower and Chinese cabbage (Allen *et al*., 2009). However, certain crop cultivars such as broccoli have been shown to differ in their susceptibilities to swede midge damage (Hallett, 2007). Nevertheless, Andreassen *et al*. (2018) found no differences in crop susceptibility or host plant resistance to swede midge damage for fourteen commercial cultivars of *Brassica napus* L. and several other widely-grown *Brassica* species in western Canada.

1.4 Physical control

Physical exclusion techniques, such as insect netting, can be used to reduce/prevent crop damage by *C. nasturtii* in fields that have been free from infestations for two–three years. However, the use of insect nettling is expensive, unfeasible for large-scale operations and may create adverse microclimatic conditions (Wyss and Daniel, 2004; Hodgdon *et al*., 2017). Nevertheless, exclusion netting may have some benefit for small-scale organic crop production; particularly when growers are unable to carry out adequate crop rotations (Hodgdon *et al*., 2017). In organic systems, to ensure that the netting does not have to be removed for weeding, a mulch can be used to manage weed populations. This reduces the number of opportunities that *C. nasturtii* has to enter the crop (Hodgdon *et al*., 2017). In addition, Wyss and Daniel (2004) found that mesh fencing (height of 1.4 m) can reduce the damage caused by *C. nasturtii* in broccoli as it is a relatively low-flying insect. Conversely, Hodgdon *et al*. (2017) showed that exclusion fencing did not provide effective control in the field, as adults were likely carried over the fencing by the wind.

1.5 Chemical control

The control of *C. nasturtii* larvae with conventional synthetic chemical insecticides with contact action often has limited success. This is because larvae regularly feed on inaccessible parts of the plant (*e.g.* in the folds of apical buds) (Chen *et al*., 2011). Generally, adult midges are easier to target with contact treatments, however, due to their short life spans, timing is crucial for insecticide application (Lole, 2005). It is important to control the first generation of midges to reduce the number of individuals that go on to produce subsequent generations (Hallett *et al*., 2008). Additionally, managing infestations of *C. nasturtii* with conventional synthetic chemical insecticides is most effective during the early stage of host plant colonisation due to lower populations (Hallett *et al.,* 2009a; Chen *et al*., 2011).

In Europe, the timing of insecticide application may be informed by the Contapré model, which uses day-degrees (DD) to predict the emergence of adult swede midge (Bouma, 1996). The model is based on the mean daily soil temperature at a depth of 5 cm and the lower threshold for midge development of 7.2°C. The model starts to accumulate day degrees when daily maximum soil temperature (at a depth of 5 cm) exceeds 20°C and there is ≥11 mm of rain within three days (Hallett *et al.*, 2008). Adults are expected to emerge once 160 DD have been accumulated.

Validation of the model was carried out in Germany under irrigated field conditions (Koch and Gemmar, 2002). Model predictions were accurate within 2–3 days. However, the Contapré model did not perform accurately in Canada under non-irrigated conditions. It is possible that this was due to there being more than one emergence type (Hallett *et al.*, 2008) and/or a delay in pupal development in dry soils during periods of low or no rainfall. In Canada, an alternative forecasting system (MidgEmerge) is employed (Hallett *et al.*, 2008).

Alternatively, the application of insecticides can be timed based on the capture of adult males by pheromone traps (Hallett *et al.*, 2007; Hallett and Sears, 2013). Due to the considerable variability in local adult abundance during the spring/summer (Hallett and Sears, 2013), the employment of action thresholds for timing insecticide applications can provide improvements over calendar-based spray programmes, as treatments may be applied around the peaks in adult emergence.

This approach has been shown to successfully reduce damage by *C. nasturtii* in cabbage. Here, the action threshold is based on the capture of four–ten males per pheromone trap per day with a minimum interval of one week before reapplying an insecticide (Hallett and Sears, 2013). Trap monitoring is required at least two–three times a week in order to detect increases in *C. nasturtii* captures and to optimise the timing of insecticide application. After head formation, there is less need to apply insecticides to cabbage, even when the pheromone-based action threshold is exceeded (Hallett and Sears 2013). This is because the marketable part of cabbage is no longer at risk of damage as the central meristem is now protected in the head. However, further research is required to determine effective thresholds to inform insecticide use in other *Brassica* crops.

Several studies investigating the efficacy of synthetic chemical insecticides found that the application of foliar sprays (acephate, acetamiprid, chlorpyrifos, lambda-cyhalothrin, dimethoate, methomyl, and permethrin) (Wu *et al.*, 2006; Hallett *et al.*, 2009) were effective against *C. nasturtii* larvae, and with the exception of acetamiprid, were also effective against adult midges. Soil drench treatments (acetamiprid, imidacloprid, and thiamethoxam) also provided very high levels of control of *C. nasturtii* larvae for seven weeks (Wu *et al.*, 2006). Similarly, the seed treatments, clothianidin and

thiamethoxam effectively controlled all *C. nasturtii* larvae in laboratory experiments (Wu *et al.*, 2006). In North America, recommendations for the conventional management of *C. nasturtii* are to apply systemic neonicotinoid insecticides at transplant and then to apply foliar insecticides, on a regular basis, throughout the growing season (Chen *et al.*, 2011; Hodgdon *et al.*, 2017),

In the UK, there is not a specific forecasting system in place for *C. nasturtii* and no insecticides are specifically-recommended for its control. Currently there is no evidence that insecticide resistance has developed in UK populations of *C. nasturtii*. However, there are concerns regarding the development of insecticide resistance in North American populations, where the swede midge is becoming a serious issue and insecticides are applied more widely for its control (Chen *et al.*, 2011).

1.6 Biological control

Biopesticides

With regard to organic systems, Evans and Hallett (2016) investigated the effects of several biopesticides (azadirachtin, *Beauveria bassiana,* pyrethrin and spinosad) on larval mortality, oviposition and damage symptoms of *C. nasturtii* in Ontario, Canada. In glasshouse trials, both pyrethrin and spinosad significantly reduced oviposition by *C. nasturtii* when they were applied up to 24 h before plants were exposed to adults. However, a reduction in oviposition occurred only when azadirachtin and *B. bassiana* were applied 2 h prior to exposure. Compared to the untreated controls, all treatments significantly reduced the survival of larvae when applied to cauliflower. When applied post-oviposition, spinosad led to the greatest reduction in larval survival (76%), followed by pyrethrin (62%). Furthermore, the application of spinosad in field trials in Wyss and Daniel (2004) reduced swede midge damage by 36% and 58% in broccoli and kohlrabi, respectively. However, the effects of biopesticides for the control *C. nasturtii* are often inconsistent and application may not always manage large infestations sufficiently.

The time at which biopesticides are applied is important. For example, efficacy is likely to be reduced if treatments are applied too early before oviposition due to their environmental degradation in the field by factors such as temperature, UV-light, and/or moisture (Evans and Hallett, 2016). For this reason, treatments should be applied when a sufficient number of adults are first detected in the field (*e.g.* through pheromone trap monitoring). Overall, pyrethrin and spinosad offer the greatest potential as biological control options for *C. nasturtii*.

Essential oils

It has been shown in recent laboratory studies that certain essential oils (*e.g.* garlic and eucalyptus lemon) can lead to significant reductions in larval density by affecting the host-finding behaviour of *C. nasturtii* and subsequent oviposition (Stratton *et al.,* 2019). There is potential to test these essentials oils as repellents of *C. nasturtii* in the field.

Pheromone mating disruption

Releasing large quantities of the female sex pheromone in the field may provide control of *C. nasturtii* by preventing male adults from locating females and subsequently mating. In Europe, mating disruption using pheromones has been demonstrated successfully for *C. nasturtii* in small-scale plots with Brussels sprouts and in commercial-scale fields with either broccoli or cauliflower using a stereospecific blend (Samietz *et al.*, 2012).

While the use of pheromones for mating disruption has had great success for managing lepidopteran pests (Witzgall *et al.*, 2010; Miller and Gut, 2015), the approach has not been developed commercially for the control of dipteran pests. For *C. nasturtii,* the sex pheromone is structurally complex and expensive to synthesise (Hillbur *et al.*, 2005; Samietz *et al.*, 2012; Hodgdon *et al.*, 2019b). For these reasons, the system developed by Samietz *et al.* (2012) is unlikely to be economically viable at the commercial level.

With regard to reducing costs, Hodgdon *et al.*, (2019b) investigated the behaviour of male swede midge in response to different pheromone blends in Y-tube and wind tunnel bioassays. They determined that while adult males were more greatly attracted to stereospecific blends, compared to the cheaper to synthesis racemic blends (consisting of natural and non-natural stereoisomers), all blends prevented the majority of males from mating with females.

Additionally, Hodgdon *et al.* (2019a) investigated the diel reproductive behaviour of swede midge in laboratory and field trials in Ontario, Canada. They found that female adults release sex pheromones almost immediately after they emerge from the soil, mostly during the first five hours after dawn. Male adults were also the most active during this period, suggesting that this is when mating primarily occurs. This information could be used to design more efficient pheromone mating disruption systems. For example, turning off dispensers at times of low reproductive behaviour (*e.g.* midday and night) could help to reduce overall costs.

Natural enemies

Currently no specialist predators, parasitoids, or other natural enemies have been identified for *C. nasturtii* in Europe (Abram *et al*., 2012). While several species of parasitoid wasp use *C. nasturtii* as a host, they lack specialisation and parasitism occurs only at low levels in the field (Abram *et al*., 2012).

In the laboratory, Corlay *et al.* (2007) investigated the use of entomopathogenic nematodes and coccinellid predators for managing *C. nasturtii*. They found that both species of natural enemy reduced midge survival under controlled conditions. In particular, the inoculation of entomopathogenic nematode *Heterorhabditis bacteriophora* (at rate of 1000 infective juveniles per larva) led to 90–100% mortality in *C. nasturtii* in a range of soil types. However, in the field, the efficacy of these natural enemies was not tested. In another study, Evans *et al.* (2015) investigated the use of entomopathogenic nematodes (*Heterorhabditis bacteriophora, Steinernema carpocapsae,* and *Steinernema feltiae*) in the field to manage the pupae of *C. nasturtii*. However, they found that the nematodes did not consistently reduce the number of *C. nasturtii* that emerged from the soil as adults.

1.7 Summary

The management of *C. nasturtii* depends on a varied Integrated Pest Management (IPM) approach in order to manage infestations in the field with the necessary levels of efficacy and consistency (Evans and Hallett. 2016; Chen *et al.*, 2011). In organic systems, an IPM strategy is particularly important as biopesticides are often less effective than their conventional counterparts.

In North America, the control of *C. nasturtii* depends largely on crop rotation and the of use of synthetic chemical insecticides, with the timing of applications often informed by the number of adult males caught in pheromone traps (Hallett *et al*., 2007; Chen *et al*., 2011; Hallett and Sears, 2013). These management strategies would likely also be sufficient in Europe, where pest pressure by *C. nasturtii* is often lower.

Due to the low damage threshold of certain crops, mating disruption using pheromones is a promising novel approach for the control of *C. nasturtii*; however, research is still required to determine how the cost and delivery of this tactic could be optimised in the field (Hodgdon *et al.,* 2019a; 2019b). Similarly, strategies that prevent host location and subsequent oviposition by female adults (*e.g.* volatile lures or repellents) may have potential for IPM programmes going forward (Boddum *et al.*, 2018; Stratton *et al.,* 2019).

1.8 References

Abram, P. K., Haye, T., Mason, P. G., Cappuccino, N., Boivin, G. and Kuhlmann, U. (2012). Identity, distribution, and seasonal phenology of parasitoids of the swede midge, *Contarinia nasturtii* (Kieffer) (Diptera: Cecidomyiidae) in Europe. *Biological Control*, *62*(3), pp.197-205.

Allen, J., Fraser, H. and Hallett, R. (2009). The swede midge–a pest of crucifer crops. *Ontario Ministry of Agriculture and Food. Fact sheet*.

Andreassen, L., Soroka, J., Grenkow, L., Olfert, O. and Hallett, R. H (2018). Midge (Diptera: Cecidomyiidae) injury to Brassicaceae in field trials in northeastern Saskatchewan, Canada. *The Canadian Entomologist*, *150*(5), pp.637-651.

Barnes, H. F. (1946). Gall midges of economic importance, vol. 1: gall midges of root and vegetable crops. Crosby Lockwood, London, United Kingdom.

Barnes, H. F. (1950). The identity of the swede midge, with notes on its biology. *Annals of Applied Biology*, *37*(2), pp.241-248.

Boddum, T., Molnár, B. P., Hill, S. R., Birgersson, G.Á. and Hansson, B. (2018). Host attraction and selection in the swede midge (*Contarinia nasturtii*). *Frontiers in Ecology and Evolution*, 6(61), pp.1-9.

Boddum, T., Skals, N., Wirén, M., Baur, R., Rauscher, S. and Hillbur, Y. (2009). Optimisation of the pheromone blend of the swede midge, *Contarinia nasturtii*, for monitoring. *Pest Management Science*, *65*(8), pp.851-856.

Bouma, E. (1996). Contapré, prototype of a model for prediction of emerging of the swede midge (*Contarinia nasturtii*). In: *Decision Systems in Crop Protection. Muenster, Germany. 4-8.*

Chen, M. and Shelton, A. M. (2007). Impact of soil type, moisture, and depth on swede midge (Diptera: Cecidomyiidae) pupation and emergence. *Environmental Entomology*, *36*(6), pp.1349-1355.

Chen, M., Shelton, A. M., Hallett, R. H., Hoepting, C.A., Kikkert, J. R. and Wang, P. (2011). Swede midge (Diptera: Cecidomyiidae), ten years of invasion of crucifer crops in North America. *Journal of Economic Entomology*, *104*(3), pp.709-716.

Chen, M., Li, W. and Shelton, A.M. (2009). Simulated crop rotation systems control swede midge, Contarinia nasturtii. *Entomologia experimentalis et applicata*, *133*(1), pp.84-91.

Corlay, F., Boivin, G. and Bélair, G. (2007). Efficiency of natural enemies against the swede midge *Contarinia nasturtii* (Diptera: Cecidomyiidae), a new invasive species in North America. *Biological Control*, *43*(2), pp.195-201.

Des Marteaux, L. E. and Hallett, R. H. (2019). Swede midge (Diptera: Cecidomyiidae) diapause initiation under stable conditions: not a family affair. *The Canadian Entomologist*, pp.1-10.

Des Marteaux, L. E., Schmidt, J.M., Habash, M. B., and Hallett, R. H. (2015). Patterns of diapause frequency and emergence in swede midges of southern Ontario. A*gricultural and Forest Entomology*, *17,* pp.77–89.

Evans, B. G. and Hallett, R. H. (2016). Efficacy of biopesticides for management of the swede midge (Diptera: Cecidomyiidae). *Journal of Economic Entomology*, *109*(5), pp.2159-2167.

Evans, B. G., Jordan, K. S., Brownbridge, M. and Hallett, R. H. (2015). Effect of temperature and host life stage on efficacy of soil entomopathogens against the swede midge (Diptera: Cecidomyiidae). *Journal of Economic Entomology*, *108*(2), pp.473-483.

Frey, J. E., Frey, B. and Baur, R. (2004). Molecular identification of the swede midge (Diptera: Cecidomyiidae). *The Canadian Entomologist*, *136*(6), pp.771-780.

Hallett, R. H. (2007). Host plant susceptibility to the swede midge (Diptera: Cecidomyiidae). *Journal of Economic Entomology*, *100*(4), pp.1335-1343.

Hallett, R. H. and Heal, J. D. (2001). First Nearctic record of the swede midge (Diptera: Cecidomyiidae), a pest of cruciferous crops from Europe. *The Canadian Entomologist*, *133*(5), pp.713-715.

Hallett, R. H. and Sears, M. K. (2013). Pheromone-based action thresholds for control of the swede midge, *Contarinia nasturtii* (Diptera: Cecidomyiidae), and residual insecticide efficacy in cole crops. *Journal of Economic Entomology*, *106*(1), pp.267-276.

Hallett, R. H., Chen, M., Sears, M. K. and Shelton, A. M. (2009). Insecticide management strategies for control of swede midge (Diptera: Cecidomyiidae) on cole crops. *Journal of Economic Entomology*, *102*(6), pp.2241-2254.

Hallett, R. H., Goodfellow, S. A. and Heal, J. D. (2007). Monitoring and detection of the swede midge (Diptera: Cecidomyiidae). *The Canadian Entomologist*, *139*(5), pp.700-712.

Hallett, R. H., Goodfellow, S. A., Weiss, R. M. and Olfert, O. (2008). MidgEmerge, a new predictive tool, indicates the presence of multiple emergence phenotypes of the overwintered generation of swede midge. *Entomologia Experimentalis et Applicata*, *130*(1), pp.81-97.

Hillbur, Y., Celander, M., Baur, R., Rauscher, S., Haftmann, J., Franke, S. and Francke, W. (2005). Identification of the sex pheromone of the swede midge, *Contarinia nasturtii*. *Journal of Chemical Ecology*, *31*(8), pp.1807-1828.

Hodgdon, E. A., Hallett, R. H., Wallin, K. F., Stratton, C. A. and Chen, Y. H. (2019). Racemic Pheromone blends disrupt mate location in the invasive swede midge, *Contarinia nasturtii. Journal of Chemical Ecology*, pp.1-10.

Hodgdon, E. A., Chen, Y. H., Hoepting, C. A. and Hallett, R. H. (2017). Organic management of Swede midge. Available online: https://ecommons.cornell.edu/handle/1813/55087 [Accessed: October 2019].

Hodgdon, E. A., Hallett, R. H., Stratton, C. A. and Chen, Y. H. (2019a). Diel patterns of emergence and reproductive behaviour in the invasive swede midge (Diptera: Cecidomyiidae). *The Canadian Entomologist*, pp.1-11.

Hodgdon, E. A., Hallett, R. H., Wallin, K. F., Stratton, C. A. and Chen, Y. H. (2019b). Racemic pheromone blends disrupt mate location in the invasive swede midge, *Contarinia nasturtii*. *Journal of Chemical Ecology*, pp.1-10.

Koch, I. and Gemmar, A. (2002). Untersuchungen über das Auftreten und die Prognose der Kohldrehherzmücke (*Contarinia nasturtii* Kieffer) an Brokkoli in der *Vorderpfalz. Pflanzenschutzberichte* 60, pp.37-43.

Liu, J., Mori, B. A., Olfert, O. and Hallett, R. H. (2019). Determining temperature-dependent development and mortality parameters of the swede midge (Diptera: Cecidomyiidae). *Journal of Economic Entomology*, *112*(4), pp.1665–1675.

Lole, M. (2005). Swede midge control in *Brassica* crops. *HDC fact sheet 28/05*. *HDC*, East Mauling, Kent.

Miller, J. R. and Gut, L. J. (2015). Mating disruption for the 21st century: matching technology with mechanism. *Environmental Entomology*, *44*(3), pp.427-453.

Readshaw, J. L. (1961). *The biology and ecology of the swede midge Contarinia nasturii (Kieffer) (Diptera; Cecidomyidae.* Doctoral thesis, Durham University.

Readshaw, J.L. (1966). The ecology of the swede midge, *Contarinia nasturtii* (Kieff.) (Diptera, Cecidomyiidae). I.—Life-history and influence of temperature and moisture on development. *Bulletin of Entomological Research*, *56*(4), pp.685-700.

Samietz, J., Baur, R. and Hillbur, Y. (2012). Potential of synthetic sex pheromone blend for mating disruption of the swede midge, *Contarinia nasturtii*. *Journal of Chemical Ecology*, *38*(9), pp.1171-1177.

Seaman, A. J., Lange, H. W. and Shelton, A. M. (2015). Swede midge, diamondback moth, and imported cabbageworm control with insecticides allowed for organic production, 2014. *Arthropod Management Tests*, *40*(1).

Stokes, B. M. (1953). The host plant range of the swede midge (*Contarinia nasturtii* Kieffer) with special reference to types of plant damage. *European Journal of Plant Pathology*, *59*(3), pp.82-90.

Stratton, C. A., Hodgdon, E., Rodriguez-Saona, C., Shelton, A. M. and Chen, Y. H. (2019). Odors from phylogenetically-distant plants to Brassicaceae repel an herbivorous Brassica specialist. *Scientific Reports*, *9*(1), p.10621.

Stratton, C.A., Hodgdon, E. A., Zuckerman, S. G., Shelton, A. M. and Chen, Y. H. (2018). A single swede midge (Diptera: Cecidomyiidae) larva can render cauliflower unmarketable. *Journal of Insect Science*, *18*(3), p.24.

Witzgall, P., Kirsch, P. and Cork, A. (2010). Sex pheromones and their impact on pest management. *Journal of Chemical Ecology*, *36*(1), pp.80-100.

Wu, Q. J., Zhao, J. Z., Taylor, A. G. and Shelton, A. M. (2006). Evaluation of insecticides and application methods against *Contarinia nasturtii* (Diptera: Cecidomyiidae), a new invasive insect pest in the United States. *Journal of Economic Entomology*, *99*(1), pp.117-122.

Wyss, E. and Daniel, C. (2004). The effect of exclusion fences on the colonization of broccoli and kohlrabi by the Swede midge, *Contarinia nasturtii* (Diptera: Cecidomyiidae). *Mitteilungen der Deutschen Gesellschaft für allgemeine und angewandte Entomologie*, *14*(1-6), pp.387-390.